10-047-009 (REV. 6/63)

NASA CR-72908

TM 4921:68-550

DATE 4 Oct. 1968

W.O. 1140-59-0120

TECHNICAL MEMORANDUM

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TITLE: SNAP-8 Boiler Development - Evaluation of SB-1 Boiler Test Results and Proposed Design Modifications

ABSTRACT

Double-containment, single-tube, tantalum-stainless steel boiler performance characteristics were experimentally investigated under SNAP-8 system operating condition in the 1/7th Scale Loop at AGN. The results are in close agreement with predictions based on wetting and nonwetting two-phase flow models. The original boiler performance prediction based on pure dry wall boiling theory resulted in too conservative a design approach. The boiler redesign considerations leading to reduced overall mercury side pressure drop and pressure drop variation over the boiler NaK inlet temperature band are discussed.

Key Words: NaK, Mercury, Double Containment, Pressure, Temperature, Wetting, Non-wetting, Boiling Heat Transfer

APPROVED:

DEPARTMENT HEAD L. Lopez

NOTE: The information in this document is subject to revision as analysis progresses and additional data are acquired.

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I. INTRODUCTION

The major problem in the past development of the SNAP-8 boiler has been the mercury and NaK incompatibility with the 9M tube material. The evidence of excessive mercury side corrosion and NaK side embrittlement effects posed a serious limitation on the lifetime expectancy of the SNAP-8 system. As an approach to the solution of this basic problem, boilers utilizing tantalum for the mercury containment were considered. Two design concepts, namely, Ta-SS double containment and Ta-SS bimetal boilers were designed, fabricated and tested. This report deals with the experimental results of a single tube Ta-SS double-containment boiler designated SB-1. SB-1 is the 1/7 scale version of the SNAP-8 double-containment boiler configuration that was tested at NASA-LeRC, General Electric Company, and Aerojet-Azusa facility, respectively. The original thermal design and the test results of the first full-scale boiler are reported in References 1 and 6. The purpose of the SB-1 boiler operation was to investigate the heat and momentum transfer characteristics of the double-containment design concept and compare the results with full-scale boiler operation. In view of relatively complicated heat transfer and geometry between the flowing NaK and Hg in a full-scale boiler, the 1/7 scale version of the boiler permitted better NaK shell-tube skin temperature measurements which, in turn, enabled better interpretation of the thermal environment around and within the mercury flow passage. Detailed description of the SB-1 boiler assembly, test apparatus and operation is reported in Reference 7. Figure 1 is an assembly drawing of the SB-1 boiler. Reference 7 also provides the operating history of the boiler, the overall evaluation of the test results and the findings of the boiler metallurgical post test inspection.

The objective of this memorandum is to evaluate the SB-1 boiler performance chacteristics in the light of the comparative analytical results of the SNAP-8 boiler thermal design approach. The test results are compared with the original performance predictions based on dropwise dry-wall boiling theory[1] and the heat and momentum transfer correlations derived from analytical two-phase flow models, wetting and nonwetting, in a helical flow regime[2,3].

II. TEST RESULTS

The review of the SB-1 operating history and the test data summary tabulation (Table 2 and Appendix I of Reference 7) indicates that the boiler was operated for a total of 2858 hours. This time period consisted of twelve (12) start-ups and test runs. Except for the last test run (2K) the test results of all preceeding test runs exhibited various states of boiler deconditioning phenomena. The deconditioned state is assumed when the test run exhibits either low mercury exit temperature ($T_{exit} \cong T_{sat}$) and low overall mercury side pressure drop, or low overall mercury side pressure drop only. The former condition is referred to as total boiler deconditioning state. The latter condition refers to a partial boiler deconditioning state. The partial deconditioning state is manifested by poor local heat transfer rates in the plug insert section. The remainder of the boiler length, however, performs to the design expectations and the vapor superheat is available at the boiler exit.

During initial test run (#2) at 137 hours the boiler exhibited partially conditioned performance characteristics. The noted mercury exit temperature and the mercury side pressure drop increase was from 1234 to 1270°F and 30 to 56 psi, respectively. Test run #2A showed a total deconditioned state during the initial 30 hours. Thereafter the boiler performed in partially deconditioned state for 761 hours. Various total deconditioning periods from three to seven days were noted during test runs #2C to 2J until partially conditioned state of the boiler was obtained.

Prior to run 2K, the boiler Hg flow passage was cleaned per AGC Specification 10319-8B, Method 2. In addition, a leak tight loop was obtained. In view of the excellent results obtained during the run #2K which followed the cleaning operation, it is obvious that prior to initial mercury injection and during the consecutive shut-downs the mercury flow passage surface cleanliness was afflicted by various degrees of contamination. For this reason the evaluation of the test results is limited to test run #2K, the other test rusn 2A through 2J are not representation of the boilers performance.

Three data point sets from run 2K, representing steady-state operation at design NaK and Hg flow conditions, were selected to evaluate the SB-1 boiler performance characteristics. These results are designated Data Points No. 1, 2 and 3 at nominal, high and low NaK inlet temperature schedule, respectively. The test results are presented in Figures 1, 2 and 3. They show the measured NaK and Hg flow rates and the boiler terminal state conditions of the working fluids. The boiler NaK side axial temperature distribution is depicted by the NaK shell tube skin temperature measurements as shown by the legend notation. At seven (7) of the NaK shell tube axial locations the average mean temperature around the circumference of the NaK shell tube is also indicated. (The average mean temperature was established from several circumferentially spaced T/C measurements around the NaK shell tube.) These measurements show that nonuniform NaK temperature existed around the oval-round tube assembly. The mercury side pressure drop distribution in the plug insert and the swirl wire region was not measured. Only the Hg side terminal state conditions were instrumented. The boiler operation (Run 2K) demonstrated excellent steady-state performance characteristics immediately ater the startup. The Hg vapor flow exit pressure oscillations were ± 2 and ± 7 psi at high and low boiler NaK inlet temperatures, respectively. The SB-1 test suction did not employ an inlet flow restrictor (orifice) to induce a pressure drop at the mercury inlet end. It is expected that if such were employed the pressure oscillations would be reduced.

III. TEST DATA VS ANALYTICAL MODEL EVALUATION

The comparison of the experimental NaK shell skin temperature plot with the original dry-wall boiling heat transfer design profile,[1] as shown in Figure 3, labeled TN-BODEAN, indicates that the slope of the experimental data is significantly steeper than the design prediction. This discrepancy suggests that the tantalum surface was wetted by mercury, and, therefore, higher boiling heat transfer rates were obtained. For this reason, the quantitative evaluation of the SB-1 boiler test results was conducted in the light of idealized heat and momentum transfer models for helical two-phase flow regime under tube wall surface wetting conditions. The analytical and experimental work of AGC and Geoscience [2], [3] was utilized to formulate the BOiler DEsign and PErformance analysis computer code (BODEPE)[4].

In evaluating the test data by means of the BODEPE computer code, the independent variables used in calculating the predicted results were chosen to match those of the test variables wherever possible. The determination of other variables and constants not directly available from the test and analytical model interpretation was established by trial and error calculations using several SB-1 boiler data sets. These calculations refer to interface frictional pressure drop coefficient between the laminar annular liquid film at the tube wall and the turbulent vapor core in the separated helical two-phase flow model. The trial and error method estimated the interface frictional pressure drop coefficient values of .5 and .05 for the boiler plug insert and swirl wire region, respectively. These values were introduced as constants in the CODEPE computer code. The relatively large value of the interface frictional pressure drop coefficient in the plug insert region could possibly be attributed to extreme interface roughness caused by liquid film breakup in the partially agglomerated spongy spheroid layer at the tube wall. The existence of such a liquid film layer may be suggested from Geoscience observations[8] of low quality mercury boiling experiment in a tube with a transparent port.

The determination of the "vapor phase only" frictional pressure drop coefficients was based on the correlation for helical flow passage (SFHX) geometry (Reference 4, Appendix C, Section C-6). The "vapor flow only" frictional pressure drop coefficients in the swirl wire (SW) region were determined from the helical flow similarity considerations between the SW and SFHX geometry. The trial and error calculations provided $\xi_{SW} = 0.6\ \xi_{SFHX}$ which was used in the BODEPE code for 2K series test data analysis.

A comparison of experimental and analytical results of boiler performance at nominal, high and low NaK temperature schedules is shown in Figures 1, 2, and 3 respectively. The predicted operating parameters for SB-1 are shown in column marked "BODEPE FIT-1." TN-1, THG-1 and PHG-1 curves are the corresponding NaK and Hg temperature profiles and the Hg pressure profile, respectively. The points marked by (⊙) on TN curve denote 10% vapor quality increments. The predicted TN curve represents mixed mean temperature in the NaK shell tube. As expected, it falls below the NaK shell tube skin temperature measurements in the high heat flux boiling region. The discrepancies noted in particular in Figure 3 may be attributed to inaccuracies in temperature measurements.

The predicted mercury pressure profile plot, PHG-1, shows good agreement with the measured pressure drop between the boiler terminals. The comparison of the pressure drop at low (Figure 3) and high (Figure 2) NaK temperature schedule (plotted together on Figure 4) shows that significant pressure drop variation in the boiler occurred in the 4 ft long plug insert section. This variation was caused by the plug insert exit vapor quality rise from 12 to 23%. The pressure drop variation downstream of the plug insert is relatively insensitive to NaK temperature conditions. The mercury liquid-vapor interface location is the first point marked (▽) at the mercury inlet end of THG-1 curve. From there on the THG-1 curve represents saturation temperature up to 100% vapor quality point, where the vapor superheating is initiated. The analysis postulated that tantalum tube wall wetting prevailed up to 88% vapor quality. Thereafter, a droplet-rivulet flow regime was assumed.

The as built nonsymmetric stagnant NaK layer thermal resistance of the oval-round tube geometry was assumed to be a simplified concentric annular model as provided in Appendix A. The test results also suggested that primary NaK side film thermal resistance may be lower than one predicted by uniform heat input conditions.(5) For this reason, the test data were evaluated using 20% higher NaK side film heat transfer coefficient than the Reference 5 correlation provides.

The test data comparison with the predicted results (BODEPE) based on wetted boiling heat transfer and associated momentum transfer correlation showed good agreement. The results depicted in Figure 3 are representative for low NaK temperature schedule (1283°F) operation. TN-1 curve locates the boiling termination point at 19.2 ft length. The THG-1 curve locates the mercury superheat design temperature of 1253°F at 24.2 ft length. The availability of this mercury vapor temperature at 24.2 ft length suggests the boiler length reduction. Figure 2 represents the boiler operation at high NaK temperature schedule (1336°F), where the boiling terminates at 14.8 ft length (TN-1 curve) and the 30°F terminal temperature difference (TNin--THGout) results at 20.5 ft length. The comparison of low (Figure 3) and high (Figure 2) NaK temperature schedule operation reveals that significant pressure drop variation from 21.3 to 70.2 psi occurs in the plug insert vapor quality region when the plug insert vapor exit quality goes from 12 to 23%. These results imply that the magnitude of boiler total pressure drop and its variation could be reduced by shortening both the plug insert and the overall boiler length. These aspects are explored in section IV.

Typical heat transfer characteristics of the SB-1 boiler are shown in Figure 5 and 6, where the local heat flux (Q/A), the overall conductance (U) and the bulk mean NaK-to-Hg temperature difference (ΔT_{BULK}) is plotted in terms of boiler length (L) and vapor quality (x), respectively. These plots refer to test run 2K-1 and NaK temperature profile TN-1 as depicted in Figure 1. In view of the relatively high mercury side film coefficients in the preheat and wetted boiling region, the heat transfer in this area is governed by nearly constant NaK side film and tube wall thermal resistance (U = 950 to 1100 btu/h4-ft^2-°F) and the significant ΔT_{BULK} variation in the preheat section. The heat transfer in the drywall boiling region (x ≅ 88 to 100%) is, however, a strong function of relatively low and decreasing mercury side film coefficients resulting in U variation from 160 to 40 btu/hr-ft^2-°F. In the superheat region the U variation is from 92 to 80 btu/hr-ft^2-°F and the local heat fluxes are small and gradually decreasing until the boiler mercury exit end is reached. The discontinuities in the plots, noted in Figure 5 and 6, are caused by the changes in the mercury flow passage internal geometry and the utilization of different two-phase flow heat and momentum transfer models. The summary tabulation of the SB-1 boiler analysis is shown in Table 1, 2, and 3.

IV. BOILER REDESIGN CONSIDERATIONS

In view of the relatively favorable agreement between the SB-1 boiler test results and the BODEPE code predictions, this code was utilized to investigate boiler design modifications. Excessively long superheat length, relatively high pressure drop and pressure drop variation over the NaK inlet temperature band in both the full-scale SNAP-8 double-containment boilers No. 1 and 2 and the SB-1 boiler as well, certainly suggests that the plug insert and overall boiler length reduction may be beneficial. For this reason, the present double-containment geometry was studied at reduced plug insert and overall boiler length of 3 ft and 25 ft, respectively. Except for the length dimensions, the independent variables used in calculating the predicted results of this analysis, referred to as BODEPE FIT - 1A, are superimposed on the SB-1 boiler temperature and pressure profiles shown in Figures 1, 2, and 3. As can be seen from Figure 3, the total boiler length of 25 ft is sufficient to provide the necessary mercury vapor exit state conditions of 255 psia and 1250°F at low NaK temperature schedule. The plug insert length reduction from 4 to 3 ft lengths resulted in a plug insert exit quality change from 12 to 10% and overall boiler pressure drop change from 56.4 to 41.3 psi. The high NaK temperature schedule comparison is depicted in Figure 2. It shows the plug insert quality and the overall pressure drop reduction from 23 to 20% and 108.6 to 73.1 psi, respectively. Figure 1 presents the comparative data at nominal NaK temperature schedule. As can be seen from Figures 2 and 3, the assumed plug insert and overall boiler length reduction of the SB-1 boiler would reduce the mercury side pressure drop variation over the NaK inlet temperature band from 52.2 to 31.8 psi. The plug insert length reduction also results in higher pinch point temperature difference and NaK temperature profile shift towards the mercury inlet end. The summary tabulation of the analysis for the modified boiler length conditions is shown in Tables 1A, 2A and 3A. The comparative results referring to the original SB-1 boiler length are contained in Tables 1, 2 and 3. Graphical comparison of the pressure drop variation over the NaK inlet temperature band for the original (-1) and modified (-1A) SB-1 boiler length conditions, is shown in Figure 4.

Comparative plots of the plug insert vapor exit quality (x_{PL}) and the plug insert pressure drop (ΔP_{PL}) versus pinch point temperature difference (ΔT_{PP}) are depicted in Figure 7. The ΔT_{PP} range from 30 to 70°F corresponds to boiler NaK inlet temperature variation from 1280 to 1330°F, respectively. The reduction of the plug insert effective length from 4 to 3 ft is reflected in reduced plug insert pressure drop and vapor exit quality values and their variation over the NaK inlet temperature band. As a result of these pressure drop conditions the plug insert section operates at a lower level absolute pressure curve (PHG-1A, Figure 1, 2, 3) and consequently at increased pinch point temperature difference.

V. CONCLUSIONS AND RECOMMENDATIONS

Successful operation of the mercury boiler requires considerable care in maintaining purity of the system. In particular, the cleanliness of the Hg passage surfaces under vacuum conditions prior to Hg injection is of utmost importance.

Heat and momentum transfer predictions based on wetting and nonwetting two-phase flow models are in good agreement with the experimental results.

The original design predictions of dropwise dry wall boiling theory resulted in excessive conservative boiler heat transfer rates and excessive boiler length.

The consideration of reduction in the plug insert and total boiler length to 3 and 25 ft, respectively, shows that the desired Hg vaporization rate and vapor exit state can be obtained with reduced pressure drop and pressure drop variation within the prescribed boiler NaK inlet temperature band.

The non-uniform circumferential NaK shell skin temperature distribution at and on both sides of the NaK exit terminal point indicates that severe circumferential temperature non-uniformity exists around the oval-round tube mercury passage assembly. Simulated water flow tests with dye injection into present full scale SNAP-8 boiler NaK flow passage configuration at G.E.[9] are supporting this conclusion. The placement of NaK flow turbulence (mixing) promoters into the NaK flow passage up to 8 feet from the NaK exit and exiting the NaK flow through several NaK shell tube radial ports into a circular manifold is visualized as a solution to better NaK flow temperature distribution.

Based on these conclusions the following design modifications are proposed for both the 1/7 scale experimental and the full scale double containment tantalum-stainless steel boilers.

1. The total boiler length as measured between the center lines of the NaK inlet and exit ports should be reduced to 25 feet.

2. The total multipassage plug insert length should be reduced to 3.5 feet. Its location in the tantalum tube is such that the distance between the NaK exit port center line and the plug insert end point is 3.0 ft.

3. Uniform circumferential NaK temperature environment around the mercury flow passages should be provided by suitable low pressure drop NaK stream turbulence (mixing) promotors extending 5 ft beyond the end point of the plug insert.

4. To secure uniform NaK temperature in the radial planes of the stagnant NaK region the present single port NaK exit design should be modified to a radial multiport geometry which discharges the NaK into an adjacent annular or separate circular NaK receiving manifold.

NOMENCLATURE

ESH - Excess superheat section

PBI - Pressure, mercury boiler inlet, psia

PBO, PHBO - Pressure, mercury boiler out, psia

PH - Preheat section

PHG - Pressure, mercury, psia

SFHX - Single fluted helix

SW - Swirl wire

SH - Vapor superheat section

THBI - Temperature, mercury boiler in, °F

THBO - Temperature, mercury boiler out, °F

THBI - Temperature, NaK boiler in, °F

THBO - Temperature, NaK boiler out, °F

TH - Temperature, NaK, °F

U - Overall conductance, BTU/Hr-Ft^2-°F

WH - Mercury flow rate, lb/hr

WN - NaK flow rate, lb/hr

QHL - External heat loss, KW

Q/A - Heat flux, Btu/hr-ft^2

XP - Plug insert vapor quality region

XDRY - Dry wall boiling region

XWET - Wetted boiling region

ΔP_{MPP} - Pressure drop, plug insert section, psi

ΔP_{TOT} - Pressure drop, total, psi

ΔP_{SW} - Pressure drop, swirl wire region, psi

ΔT_{BULK} - Temperature difference, NaK-to-Hg, °F

ΔTNT - Temperature drop, NaK side, °F

ξ - Frictional pressure drop coefficient

REFERENCES

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8. Personal Communications to Dr. H. F. Popendiek, Geoscience Ltd.

9. Personal Communications to E. R. Furman, LeRC, NASA.

SNAP-8 SB-1 BOILER TEMPERATURE AND PRESSURE PROFILE

PAGE

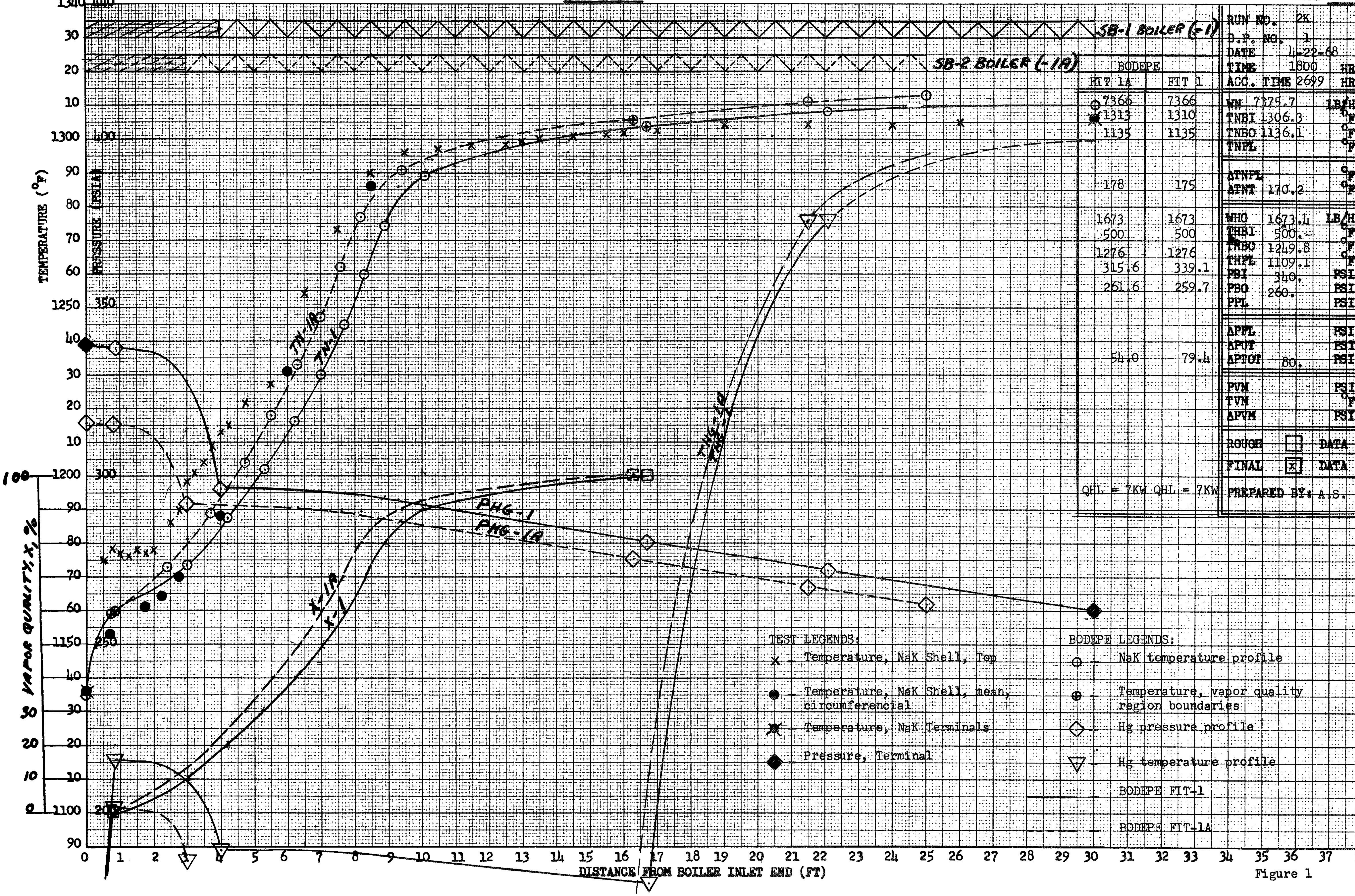


Figure 1

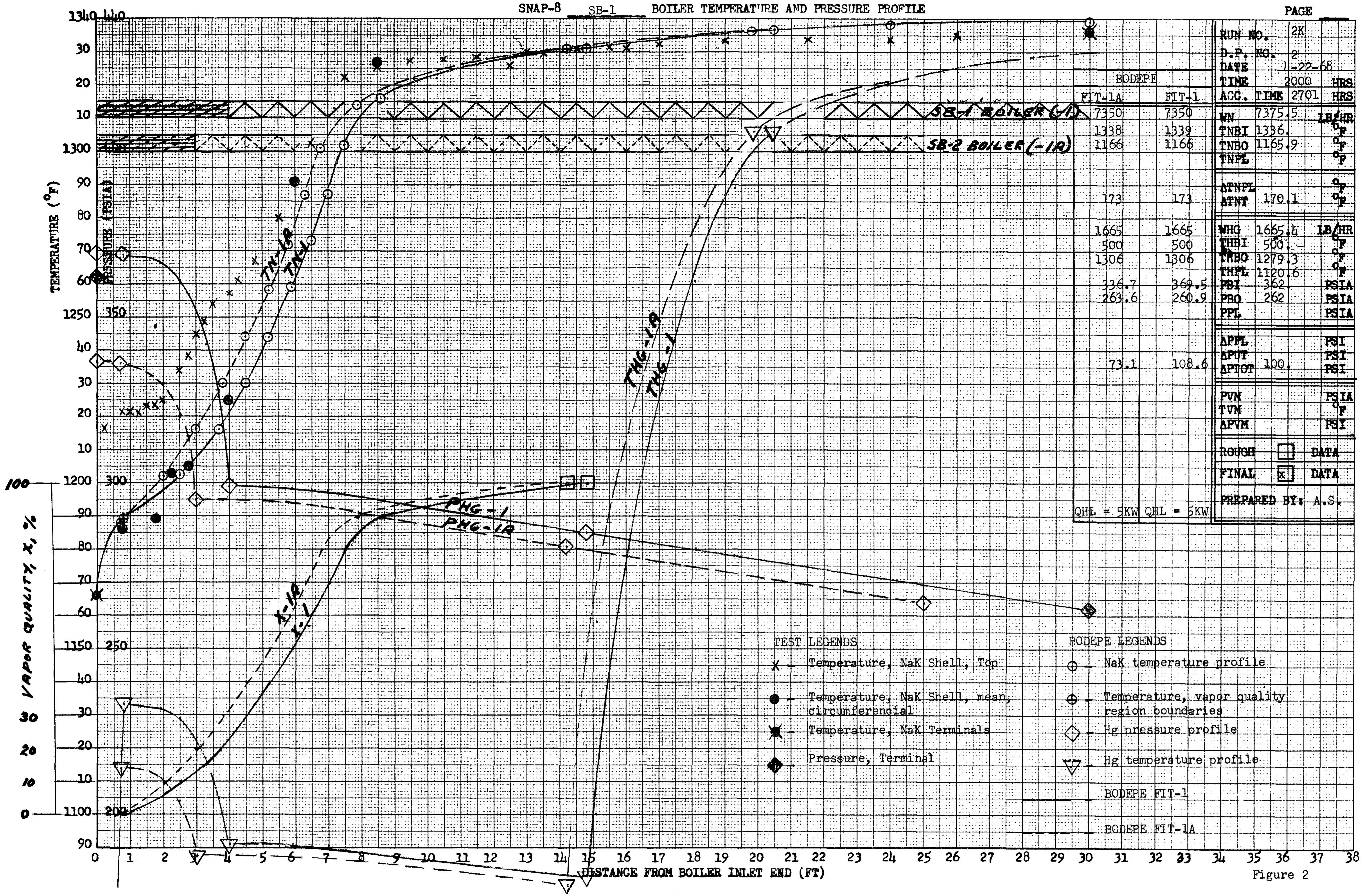
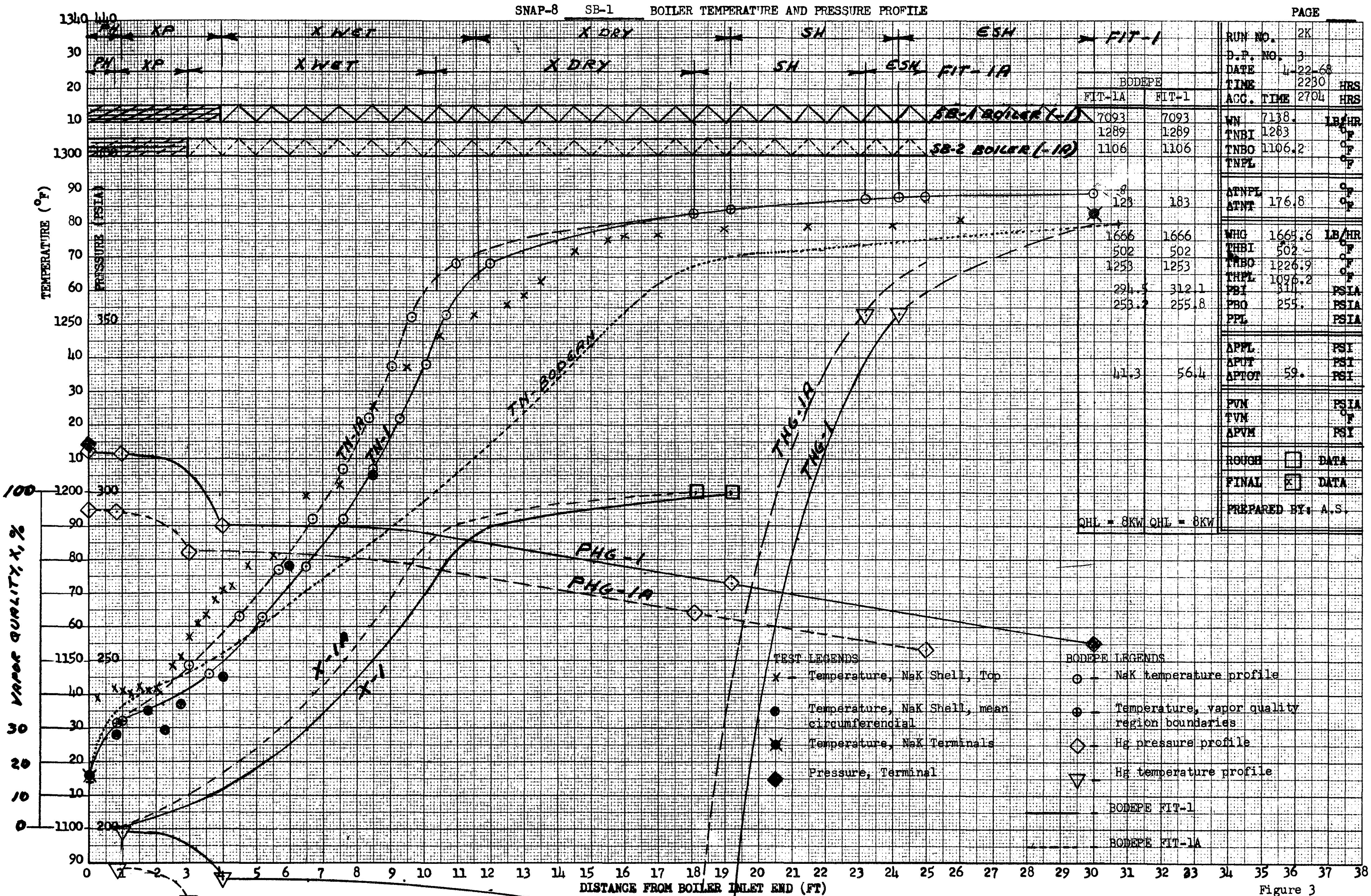
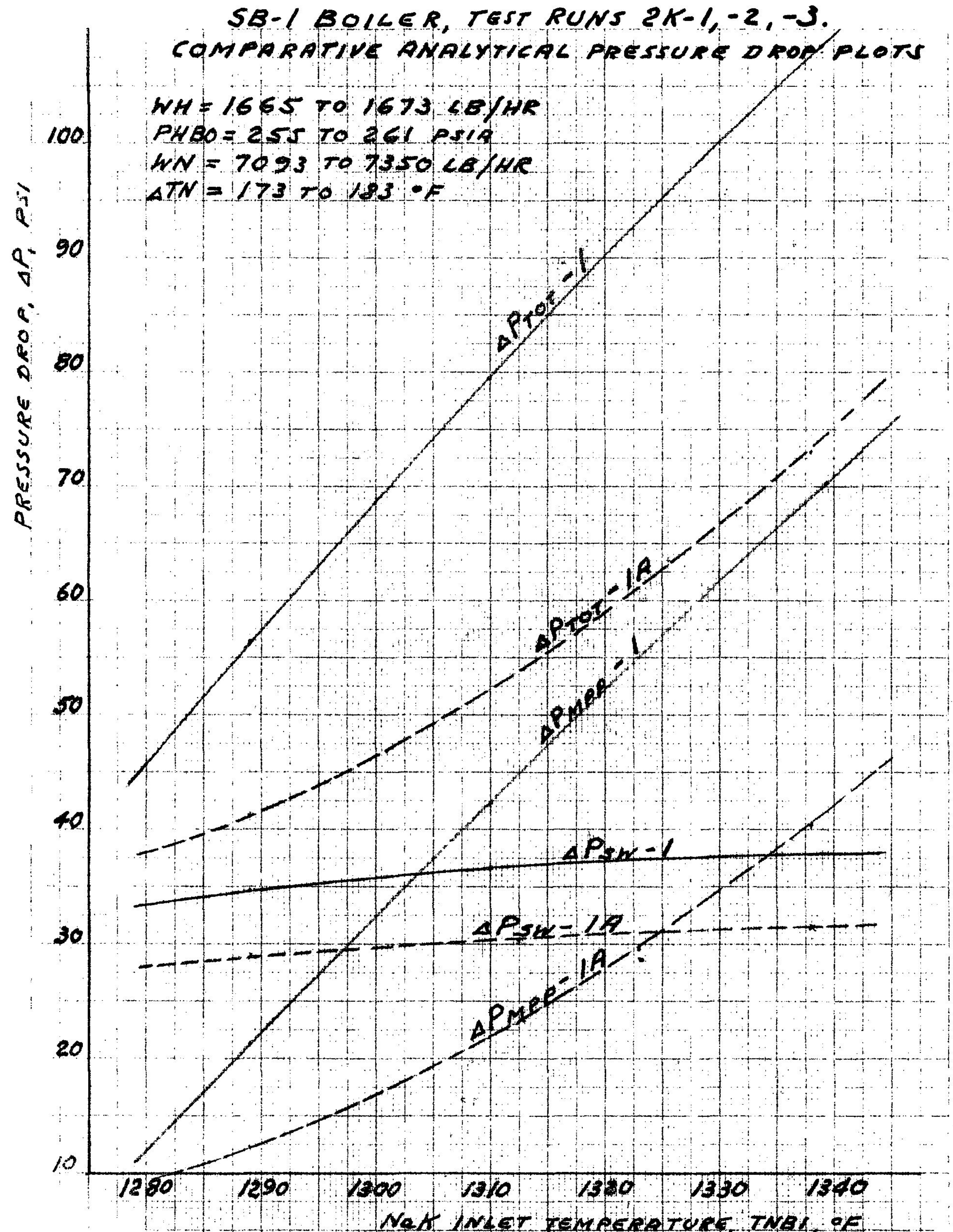

SNAP-8 SB-1 BOILER TEMPERATURE AND PRESSURE PROFILE
PAGE
RUN NO. 2K
D.P. NO. 2
DATE 1-22-68
TIME 2000 HRS
ACC. TIME 2701 HRS
BODEPE
FIT-1A
FIT-1
WN 7350 7350 7375.5 LB/HR
TNBI 1338 1339 1336. °F
TNBO 1166 1166 1165.9 °F
TNPL °F
ΔTNPL °F
ΔTNT 173 173 170.1 °F
WHG 1665 1665 1665.4 LB/HR
THBI 500 500 500. °F
THBO 1306 1306 1279.3 °F
THPL 1120.6 °F
PBI 336.7 369.5 362 PSIA
PBO 263.6 260.9 262 PSIA
PPL PSIA
ΔPPL PSI
ΔPUT PSI
ΔPTOT 73.1 108.6 100. PSI
PVN PSIA
TVM °F
ΔPVM PSI
ROUGH DATA
FINAL DATA
PREPARED BY: A.S.
QHL = 5KW QHL = 5KW
SB-1 BOILER (-1)
SB-2 BOILER (-1A)
TN-1
TN-1A
THG-1
THG-1A
PHG-1
PHG-1A
X-1
X-1A
TEMPERATURE (°F)
PRESSURE (PSIA)
VAPOR QUALITY, X, %
DISTANCE FROM BOILER INLET END (FT)
TEST LEGENDS
Temperature, NaK Shell, Top
Temperature, NaK Shell, mean, circumferencial
Temperature, NaK Terminals
Pressure, Terminal
BODEPE LEGENDS
NaK temperature profile
Temperature, vapor quality region boundaries
Hg pressure profile
Hg temperature profile
BODEPE FIT-1
BODEPE FIT-1A

Figure 2



SNAP-8 SB-1 BOILER TEMPERATURE AND PRESSURE PROFILE
PAGE
RUN NO. 2K
D.P. NO. 3
DATE 4-22-68
TIME 2230 HRS
ACC. TIME 2704 HRS
BODEPE
FIT-1A
FIT-1
WN 7138. LB/HR
TNBI 1283 °F
TNBO 1106.2 °F
TNPL °F
ΔTNPL °F
ΔTNT 176.8 °F
WHG 1665.6 LB/HR
THBI 502.- °F
THBO 1226.9 °F
THPL 1096.2 °F
PBI 311. PSIA
PBO 255. PSIA
PPL PSIA
ΔPPL PSI
ΔPUT PSI
ΔPTOT 59. PSI
PVM PSIA
TVM °F
ΔPVM PSI
ROUGH DATA
FINAL DATA
PREPARED BY: A.S.
QHL = 8KW QHL = 8KW
TEMPERATURE (°F)
PRESSURE (PSIA)
VAPOR QUALITY, X, %
DISTANCE FROM BOILER INLET END (FT)
PH XP X WET X DRY SH ESH FIT-1
PH XP X WET X DRY SH ESH FIT-1A
SB-1 BOILER (-1)
SB-2 BOILER (-1A)
TN-1A
TN-1
TN-BODEAN
THG-1A
THG-1
PHG-1
PHG-1A
X-1A
X-1
TEST LEGENDS
Temperature, NaK Shell, Top
Temperature, NaK Shell, mean circumferencial
Temperature, NaK Terminals
Pressure, Terminal
BODEPE LEGENDS
NaK temperature profile
Temperature, vapor quality region boundaries
Hg pressure profile
Hg temperature profile
BODEPE FIT-1
BODEPE FIT-1A

Figure 3



BOILER PLUG INSERT (ΔP_{MPP}) AND SWIRL WIRE (ΔP_{SW}) SECTION AND TOTAL (ΔP_{TOT}) PRESSURE DROP VS. NaK INLET (TNBI) TEMPERATURE.

FIGURE 4

SB-1 BOILER, TEST RUN 2K-1

HEAT FLUX (Q/A), OVERALL CONDUCTANCE (U) AND BULK NaK-TO-HG TEMPERATURE DIFFERENCE (ΔT_{BULK}) VS. BOILER LENGTH, (L).

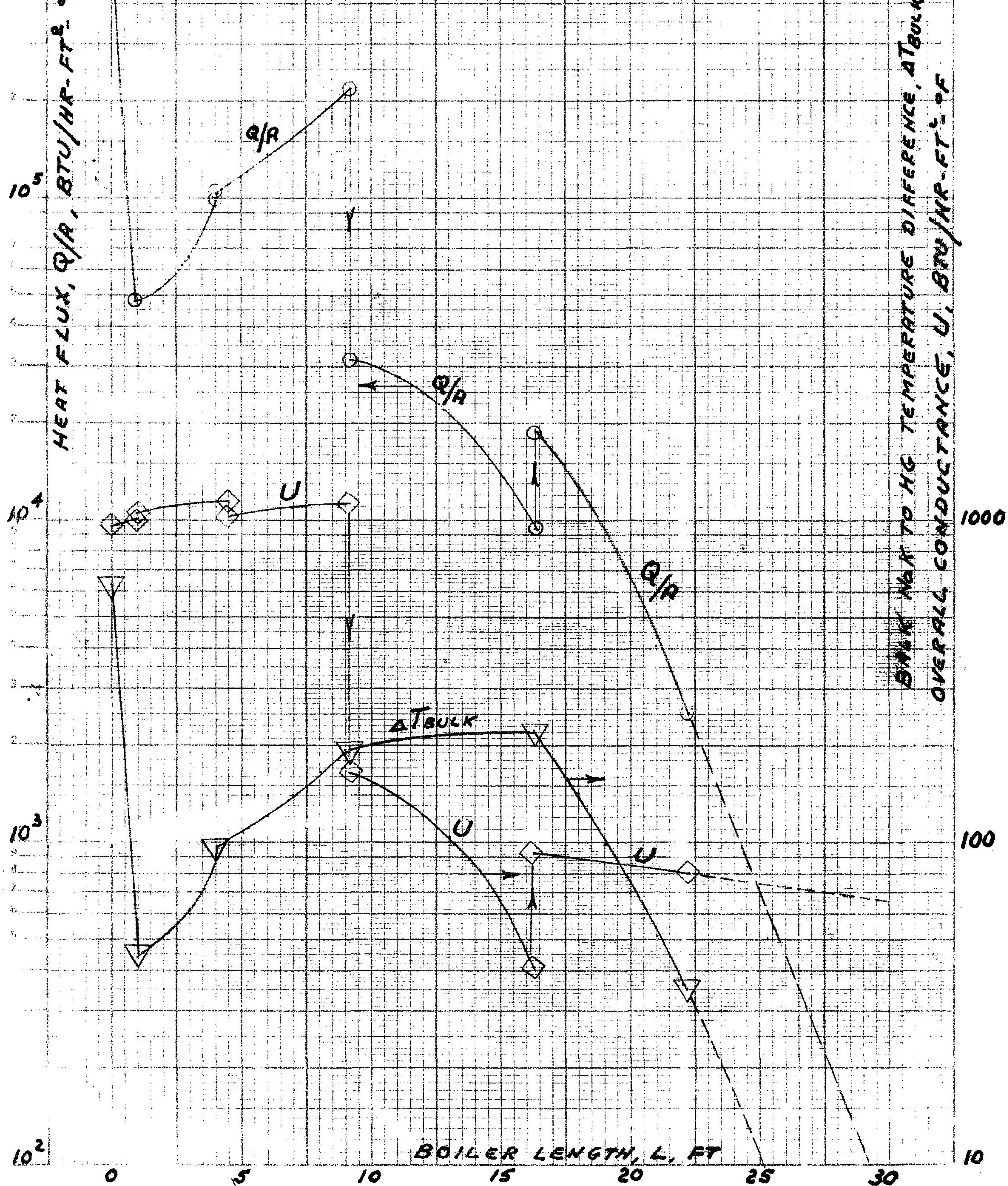


FIGURE 5

SB-1 BOILER, TEST RUN 2K-1

HEAT FLUX (Q/A), OVERALL CONDUCTANCE (U) AND BULK NaK-TO-HG TEMPERATURE DIFFERENCE (ΔT_{BULK}) VS. VAPOR QUALITY (X).

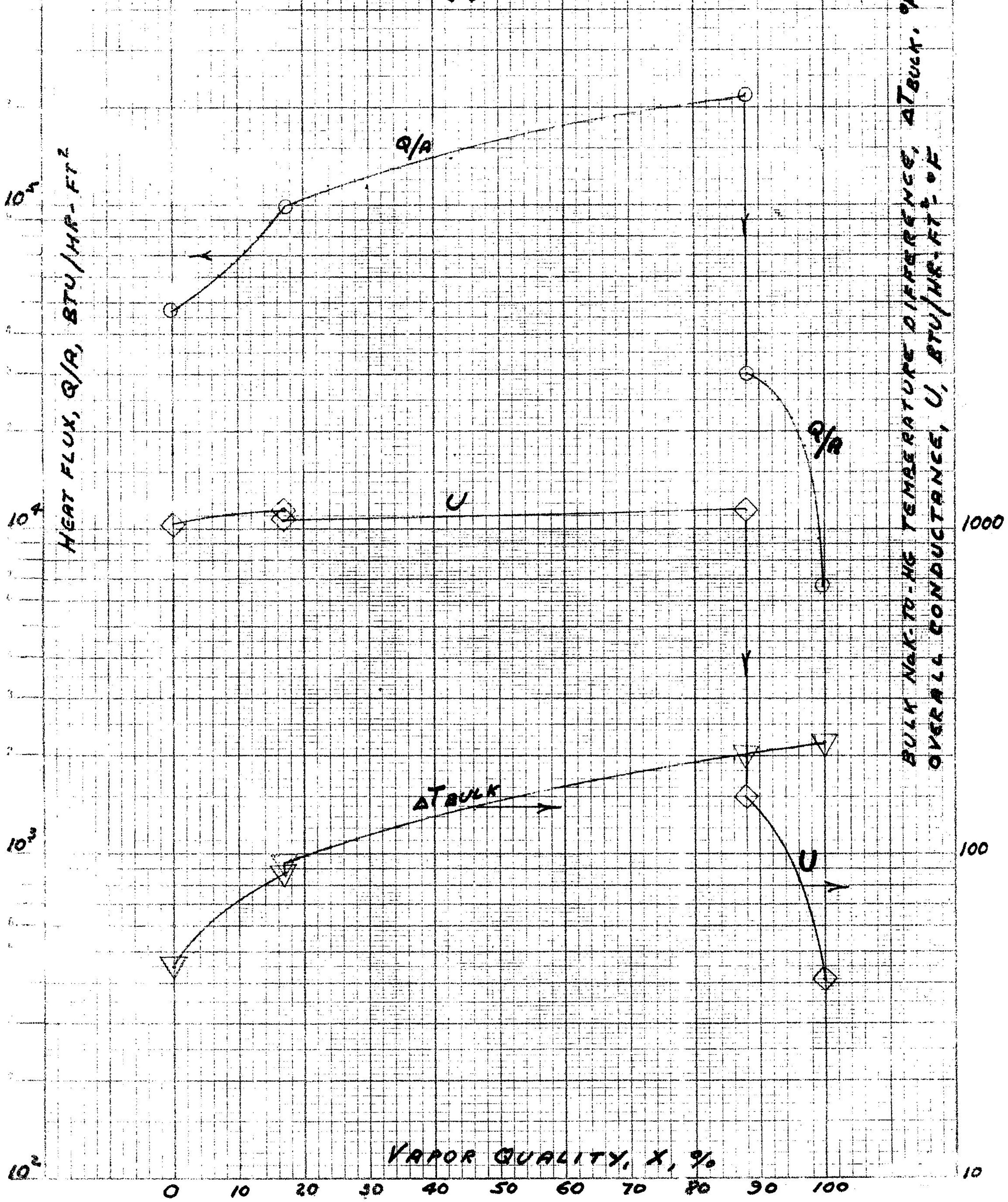


FIGURE 6

SB-1 BOILER TEST

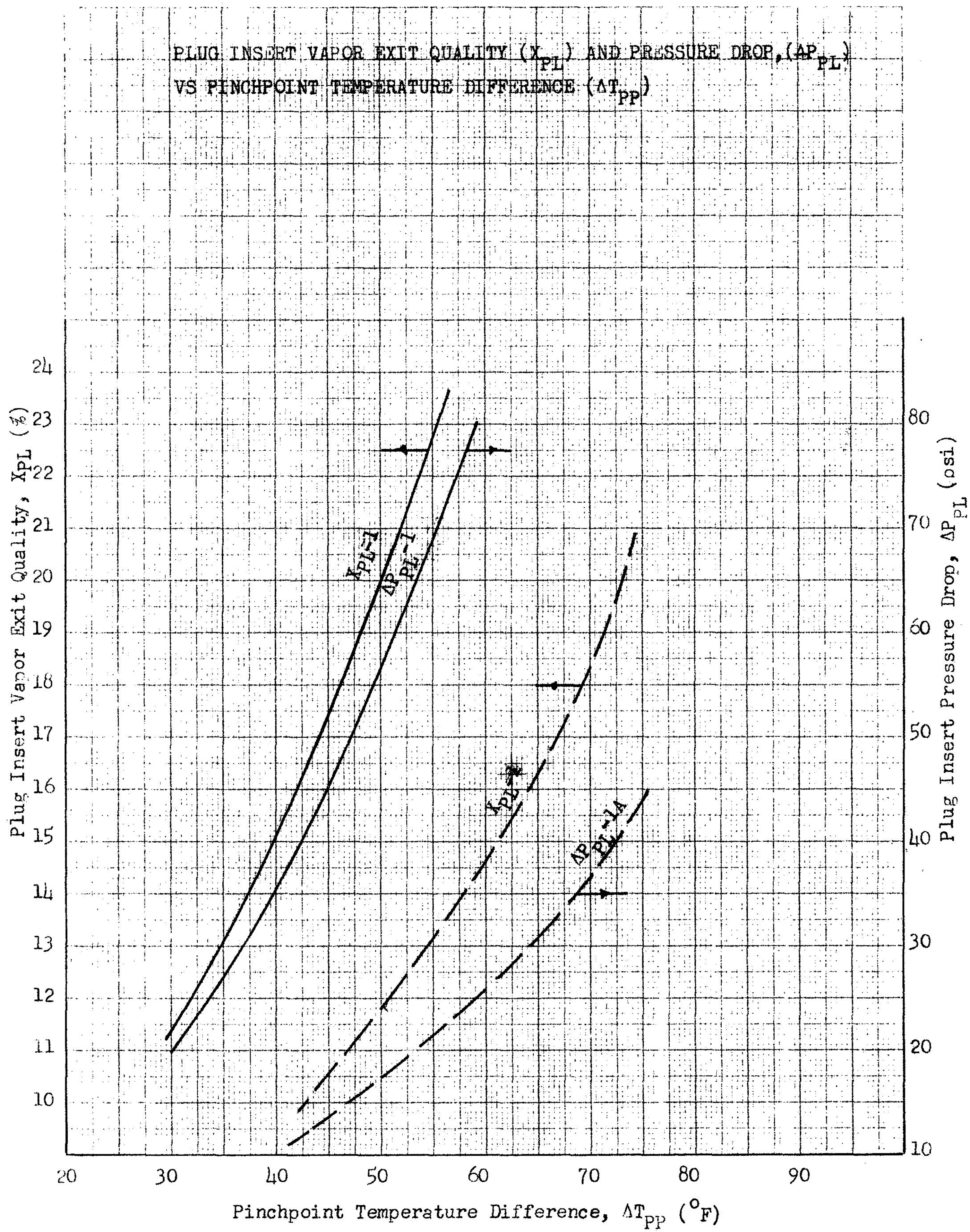


Figure 7

TABLE 1

SNAP-8 BODEPE COMPUTER PROGRAM - BOILER DESIGN AND PERFORMANCE ANALYSIS OUTPUT 1

DATE 09-09-68 S3-1 BOILER, TEST RUN 2K-1, COMPARATIVE ANALYTICAL RESULTS,FIT-1

S U M M A R Y

	LENGTH FT	INLET PRESSURE PSIA	PRESSURE DROP PSI	MEAN HEAT FLUX B/H-SQFT	NAK TEMP SECT.IN DEG.F	HG TEMP SECT.IN DEG.F	MASS VELOCITY LB/S-SQFT	HEAT INPUT B/HR	X EXIT
MPPPH SECTION	0.9	339.1	0.5	219253.	1135.	500.	824.6	33681.	0.0
MPPXP SECTION	3.1	338.6	42.2	65023.	1160.	1116.	824.6	35633.	0.17
SFHXX SECTION	12.7	296.4	15.8	75615.	1185.	1090.	233.0	168883.	1.00
SFHXSH SECTION	5.4	280.6	8.2	8778.	1304.	1079.	233.0	8239.	
EXCESSH SECTION	7.9	272.4	12.7		1310.	1276.	233.0		
TOTAL BOILER	30.0	* 259.7	79.4		* 1310.	* 1276.		246436.	

* - EXIT PARAMETERS

NAK FLOW TOTAL LB/HR	NAK FLOW NET LB/HR	MERCURY FLOW LB/HR	ENTHALPY CHANGE NAK BTU/LB	ENTHALPY CHANGE HG BTU/LB	THERMAL POWER KW	HEAT LOSS EXTERNAL KW	PINCH POINT DT DEG.F	TERMINAL NAK-HG DT DEG.F	VAPOR SUPERHEAT DEG.F
7366.	6714.	1673.	37.	147.	81.	7.	44.1	34.1	212.

THERMAL PASS RESISTANCES,MATERIAL CONDUCTIVITIES AND HG PASSAGE GEOMETRY

RCNF = 0.000219	HR-SQFT-DEG.F/BTU	NAK FILM	DI = 0.670	INCH	HG TUBE ID
RCNT = 0.000153	HR-SQFT-DEG.F/BTU	SS TUBE	TTA = 0.040	INCH	TA WALL THICKNESS
RCST = 0.000440	HR-SQFT-DEG.F/BTU	STAGNANT NAK	TST = 0.100	INCH	STAGN.NAK THICKNESS(MEAN)
RCHT = 0.000079	HR-SQFT-DEG.F/BTU	TA TUBE	TSS = 0.035	INCH	SS WALL THICKNESS
RR = 0.000890	HR-SQFT-DEG.F/BTU	TOTAL OF ABOVE	D2 = 1.020	INCH	HG TUBE OD.

PMPP = 6.000	INCH	MPP PITCH	KSS =13.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,SS
N2 = 16.		NUMBER OF PASSAGES IN MPP	KNAK =15.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,NAK
DMPP = 0.080	INCH	PASSAGE WIDTH	KTA =40.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,TA
HMPP = 0.032	INCH	PASSAGE HEIGTH(1)	DEMPP= 0.0752	INCH	DIA.EQ.,MPP
HHMPP = 0.072	INCH	PASSAGE HEIGTH(2)	ACMPP= 0.0051	SQINCH	CROSSECT.AREA
PHELIX= 2.000	INCH	SFHX PITCH	DEH = 0.5426	INCH	DIA.EQ.,SFHX
THICK = 0.001	INCH	SFHX STRIP THICKNESS	AH = 0.2873	SQINCH	CROSSECT.AREA
DBAR = 0.0	INCH	CENTER BAR OD	NI = 1.		NUMBER OF TUBES

TABLE 1A

SNAP-8 BODEPE COMPUTER PROGRAM - BOILER DESIGN AND PERFORMANCE ANALYSIS   OUTPUT 1

DATE 09-09-68   SE-1 BOILER, TEST RUN 2K-1, COMPARATIVE ANALYTICAL RESULTS,FIT-1A

S U M M A R Y

	LENGTH FT	INLET PRESSURE PSIA	PRESSURE DROP PSI	MEAN HEAT FLUX B/H-SQFT	NAK TEMP SECT.IN DEG.F	HG TEMP SECT.IN DEG.F	MASS VELOCITY LB/S-SQFT	HEAT INPUT B/HR	X EXIT
MPPPH SECTION	0.8	315.6	0.4	238544.	1135.	500.	824.6	32880.	0.0
MPPXP SECTION	2.2	315.2	23.4	76411.	1159.	1102.	824.6	29677.	0.14
SFHXX SECTION	13.3	291.8	16.4	75751.	1181.	1087.	233.0	177161.	1.00
SFHXSH SECTION	5.2	275.4	8.1	9211.	1307.	1075.	233.0	8391.	
EXCESSH SECTION	3.5	267.3	5.7		1313.	1276.	233.0		
TOTAL BOILER	25.0	* 261.6	54.0		* 1313.	* 1276.		248108.	

* - EXIT PARAMETERS

NAK FLOW TOTAL LB/HR	NAK FLOW NET LB/HR	MERCURY FLOW LB/HR	ENTHALPY CHANGE NAK BTU/LB	ENTHALPY CHANGE HG BTU/LB	THERMAL POWER KW	HEAT LOSS EXTERNAL KW	PINCH POINT DT DEG.F	TERMINAL NAK-HG DT DEG.F	VAPOR SUPERHEAT DEG.F
7366.	6714.	1673.	38.	147.	82.	7.	57.8	36.8	210.

THERMAL PASS RESISTANCES,MATERIAL CONDUCTIVITIES AND HG PASSAGE GEOMETRY

RCNF = 0.000219	HR-SQFT-DEG.F/BTU	NAK FILM	D1 = 0.670	INCH	HG TUBE ID
RCNT = 0.000153	HR-SQFT-DEG.F/BTU	SS TUBE	TTA = 0.040	INCH	TA WALL THICKNESS
RCST = 0.000440	HR-SQFT-DEG.F/BTU	STAGNANT NAK	TST = 0.100	INCH	STAGN.NAK THICKNESS(MEAN)
RCHT = 0.000079	HR-SQFT-DEG.F/BTU	TA TUBE	TSS = 0.035	INCH	SS WALL THICKNESS
RR = 0.000890	HR-SQFT-DEG.F/BTU	TOTAL OF ABOVE	D2 = 1.020	INCH	HG TUBE OD.

FMPP = 6.000	INCH	MPP PITCH	KSS =13.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,SS
N2 = 16.		NUMBER OF PASSAGES IN MPP	KNAK =15.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,NAK
CMPP = 0.080	INCH	PASSAGE WIDTH	KTA =40.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,TA
HMPF = 0.032	INCH	PASSAGE HEIGTH(1)	DEMPP= 0.0752	INCH	DIA.EQ.,MPP
HHMPP = 0.072	INCH	PASSAGE HEIGTH(2)	ACMPP= 0.0051	SQINCH	CROSSECT.AREA
PHELIX= 2.000	INCH	SFHX PITCH	DEH = 0.5426	INCH	DIA.EQ.,SFHX
THICK = 0.001	INCH	SFHX STRIP THICKNESS	AH = 0.2873	SQINCH	CROSSECT.AREA
DBAR = 0.0	INCH	CENTER BAR OD	N1 = 1.		NUMBER OF TUBES

TABLE 2

SNAP-8 BODERF COMPUTER PROGRAM - BOILER DESIGN AND PERFORMANCE ANALYSIS OUTPUT 1

DATE 09-09-68 SB-1 BOILER, TEST RUN 2K-2, COMPARATIVE ANALYTICAL RESULTS,FIT-1

SUMMARY

	LENGTH FT	INLET PRESSURE PSIA	PRESSURE DROP PSI	MEAN HEAT FLUX B/H-SQFT	NAK TEMP SECT.IN DEG.F	HG TEMP SECT.IN DEG.F	MASS VELOCITY LB/S-SQFT	HEAT INPUT B/HR	X EXIT
MPPPH SECTION	0.8	369.5	0.4	242666.	1166.	500.	820.7	34507.	0.0
MPPXP SECTION	3.2	369.1	70.2	84596.	1189.	1133.	820.7	47325.	0.23
SFHXX SECTION	10.8	298.9	14.1	82421.	1222.	1091.	231.8	155758.	1.00
SFHXSH SECTION	5.7	284.8	8.6	9322.	1331.	1082.	231.8	9330.	
EXCESSH SECTION	9.5	276.1	15.3		1339.	1306.	231.8		
TOTAL BOILER	30.0	* 260.9	108.6		* 1339.	* 1306.		246920.	

* - EXIT PARAMETERS

NAK FLOW TOTAL LB/HR	NAK FLOW NET LB/HR	MERCURY FLOW LB/HR	ENTHALPY CHANGE NAK BTU/LB	ENTHALPY CHANGE HG BTU/LB	THERMAL POWER KW	HEAT LOSS EXTERNAL KW	PINCH POINT DT DEG.F	TERMINAL NAK-HG DT DEG.F	VAPOR SUPERHEAT DEG.F
7350.	6873.	1665.	36.	148.	78.	5.	55.5	32.9	241.

THERMAL PASS RESISTANCES,MATERIAL CONDUCTIVITIES AND HG PASSAGE GEOMETRY

RCNF = 0.000219	HR-SQFT-DEG.F/BTU	NAK FILM	D1 = 0.670	INCH	HG TUBE ID
RCNT = 0.000153	HR-SQFT-DEG.F/BTU	SS TUBE	TTA = 0.040	INCH	TA WALL THICKNESS
RCST = 0.000440	HR-SQFT-DEG.F/BTU	STAGNANT NAK	TST = 0.100	INCH	STAGN.NAK THICKNESS(MEAN)
RCHT = 0.000079	HR-SQFT-DEG.F/BTU	TA TUBE	TSS = 0.035	INCH	SS WALL THICKNESS
RR = 0.000890	HR-SQFT-DEG.F/BTU	TOTAL OF ABOVE	D2 = 1.020	INCH	HG TUBE OD.

PMPP = 6.000	INCH	MPP PITCH	KSS =13.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,SS
N2 = 16.		NUMBER OF PASSAGES IN MPP	KNAK =15.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,NAK
DMPP = 0.080	INCH	PASSAGE WIDTH	KTA =40.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,TA
HMPP = 0.032	INCH	PASSAGE HEIGTH(1)	DEMPP= 0.0752	INCH	DIA.EQ.,MPP
HHMPP = 0.072	INCH	PASSAGE HEIGTH(2)	ACMPP= 0.0051	SQINCH	CROSSECT.AREA
PHELIX= 2.000	INCH	SFHX PITCH	DEH = 0.5426	INCH	DIA.EQ.,SFHX
THICK = 0.001	INCH	SFHX STRIP THICKNESS	AH = 0.2873	SQINCH	CROSSECT.AREA
DBAR = 0.0	INCH	CENTER BAR OD	N1 = 1.		NUMBER OF TUBES

TABLE 2A

SNAP-8 BODEPE COMPUTER PROGRAM - BOILER DESIGN AND PERFORMANCE ANALYSIS OUTPUT 1

DATE 09-09-68 SB-1 BOILER, TEST RUN 2K-2, COMPARATIVE ANALYTICAL RESULTS,FIT-1A

S U M M A R Y

	LENGTH FT	INLET PRESSURE PSIA	PRESSURE DROP PSI	MEAN HEAT FLUX B/H-SQFT	NAK TEMP SECT.IN DEG.F	HG TEMP SECT.IN DEG.F	MASS VELOCITY LB/S-SQFT	HEAT INPUT B/HR	X EXIT
MPPPH SECTION	0.7	336.7	0.4	266126.	1166.	500.	820.7	33442.	0.0
MPPXP SECTION	2.3	336.4	41.3	59883.	1188.	1115.	820.7	40009.	0.20
SFHXX SECTION	11.2	295.1	14.4	83797.	1216.	1089.	231.8	163985.	1.00
SFHXSH SECTION	5.8	280.7	8.9	9307.	1331.	1079.	231.8	9446.	
EXCESSH SECTION	5.1	271.8	8.2		1338.	1306.	231.8		
TOTAL BOILER	25.0	* 263.6	73.1		* 1338.	* 1306.		246881.	

* - EXIT PARAMETERS

NAK FLOW TOTAL LB/HR	NAK FLOW NET LB/HR	MERCURY FLOW LB/HR	ENTHALPY CHANGE NAK BTU/LB	ENTHALPY CHANGE HG BTU/LB	THERMAL POWER KW	HEAT LOSS EXTERNAL KW	PINCH POINT DT DEG.F	TERMINAL NAK-HG DT DEG.F	VAPOR SUPERHEAT DEG.F
7350.	6873.	1665.	36.	148.	78.	5.	73.7	32.3	239.

THERMAL PASS RESISTANCES,MATERIAL CONDUCTIVITIES AND HG PASSAGE GEOMETRY

RCNF = 0.000219	HR-SQFT-DEG.F/BTU	NAK FILM	D1 = 0.670	INCH	HG TUBE ID	
RCNT = 0.000153	HR-SQFT-DEG.F/BTU	SS TUBE	TTA = 0.040	INCH	TA WALL THICKNESS	
RCST = 0.000440	HR-SQFT-DEG.F/BTU	STAGNANT NAK	TST = 0.100	INCH	STAGN.NAK THICKNESS(MEAN)	
RCHT = 0.000079	HR-SQFT-DEG.F/BTU	TA TUBE	TSS = 0.035	INCH	SS WALL THICKNESS	
RR = 0.000890	HR-SQFT-DEG.F/BTU	TOTAL OF ABOVE	D2 = 1.020	INCH	HG TUBE OD.	

PMPP = 6.000 INCH	MPP PITCH	KSS =13.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,SS
N2 = 16.	NUMBER OF PASSAGES IN MPP	KNAK =15.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,NAK
DMPP = 0.080 INCH	PASSAGE WIDTH	KTA =40.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,TA
HMPP = 0.032 INCH	PASSAGE HEIGTH(1)	DEMPP= 0.0752	INCH	DIA.EQ.,MPP
HHMPP = 0.072 INCH	PASSAGE HEIGTH(2)	ACMPP= 0.0051	SQINCH	CROSSECT.AREA
PHELIX= 2.000 INCH	SFHX PITCH	DEH = 0.5426	INCH	DIA.EQ.,SFHX
THICK = 0.001 INCH	SFHX STRIP THICKNESS	AH = 0.2873	SQINCH	CROSSECT.AREA
DEAR = 0.0 INCH	CENTER BAR OD	N1 = 1.		NUMBER OF TUBES

TABLE 3

SNAP-8 RODERS COMPUTER PROGRAM - BOILER DESIGN AND PERFORMANCE ANALYSIS OUTPUT 1

DATE 09-09-68 SB-1 BOILER, TEST RUN 2K-3, COMPARATIVE ANALYTICAL RESULTS,FIT-1

S U M M A R Y

	LENGTH FT	INLET PRESSURE PSIA	PRESSURE DROP PSI	MEAN HEAT FLUX B/H-SQFT	NAK TEMP SECT.IN DEG.F	HG TEMP SECT.IN DEG.F	MASS VELOCITY LB/S-SQFT	HEAT INPUT B/HR	X EXIT
MPPPH SECTION	1.0	312.1	0.5	193212.	1106.	502.	321.2	32513.	0.0
MPPXP SECTION	3.0	311.6	21.3	46303.	1132.	1099.	321.2	24695.	0.12
SFHXX SECTION	15.2	290.3	17.5	67703.	1152.	1086.	232.0	180537.	1.00
SFHXSH SECTION	5.0	272.8	7.7	8506.	1284.	1074.	232.0	7472.	
EXCESSH SECTION	5.8	265.1	9.4		1289.	1253.	232.0		
TOTAL BOILER	30.0	* 255.8	56.4		* 1289.	* 1253.		245217.	

* - EXIT PARAMETERS

NAK FLOW TOTAL LB/HR	NAK FLOW NET LB/HR	MERCURY FLOW LB/HR	ENTHALPY CHANGE NAK BTU/LB	ENTHALPY CHANGE HG BTU/LB	THERMAL POWER KW	HEAT LOSS EXTERNAL KW	PINCH POINT DT DEG.F	TERMINAL NAK-HG DT DEG.F	VAPOR SUPERHEAT DEG.F
7093.	6379.	1666.	39.	146.	82.	8.	32.2	36.1	192.

THERMAL PASS RESISTANCES,MATERIAL CONDUCTIVITIES AND HG PASSAGE GEOMETRY

RCNF = 0.000219	HR-SQFT-DEG.F/BTU	NAK FILM	D1 = 0.670	INCH	HG TUBE ID
RCNT = 0.000153	HR-SQFT-DEG.F/BTU	SS TUBE	TTA = 0.040	INCH	TA WALL THICKNESS
RCST = 0.000440	HR-SQFT-DEG.F/BTU	STAGNANT NAK	TST = 0.100	INCH	STAGN.NAK THICKNESS(MEAN)
RCHT = 0.000079	HR-SQFT-DEG.F/BTU	TA TUBE	TSS = 0.035	INCH	SS WALL THICKNESS
RR = 0.000890	HR-SQFT-DEG.F/BTU	TOTAL OF ABOVE	D2 = 1.020	INCH	HG TUBE OD.

PMPP = 6.000	INCH	MPP PITCH	KSS =13.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,SS
N2 = 16.		NUMBER OF PASSAGES IN MPP	KNAK =15.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,NAK
DMPP = 0.080	INCH	PASSAGE WIDTH	KTA =40.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,TA
HMPP = 0.032	INCH	PASSAGE HEIGTH(1)	DEMPP= 0.0752	INCH	DIA.EQ.,MPP
HHMPP = 0.072	INCH	PASSAGE HEIGTH(2)	ACMPP= 0.0051	SQINCH	CROSSECT.AREA
PHELIX= 2.000	INCH	SFHX PITCH	DEH = 0.5426	INCH	DIA.EQ.,SFHX
THICK = 0.001	INCH	SFHX STRIP THICKNESS	AH = 0.2873	SQINCH	CROSSECT.AREA
DBAR = 0.0	INCH	CENTER BAR OD	N1 = 1.		NUMBER OF TUBES

TABLE 3A

SNAP-8 BODEPE COMPUTER PROGRAM - BOILER DESIGN AND PERFORMANCE ANALYSIS OUTPUT 1

DATE 09-09-68 SE-1 BOILER, TEST RUN 2K-3, COMPARATIVE ANALYTICAL RESULTS,FIT-1A

S U M M A R Y

	LENGTH FT	INLET PRESSURE PSIA	PRESSURE DROP PSI	MEAN HEAT FLUX B/H-SQFT	NAK TEMP SECT.IN DEG.F	HG TEMP SECT.IN DEG.F	MASS VELOCITY LB/S-SQFT	HEAT INPUT B/HR	X EXIT
MPPFH SECTION	0.9	294.5	0.4	210409.	1106.	502.	821.2	31882.	0.0
MPPXP SECTION	2.1	294.1	12.2	56108.	1131.	1088.	821.2	21023.	0.10
SFHXX SECTION	15.1	281.9	17.6	69767.	1149.	1080.	232.0	184714.	1.00
SFHXSH SECTION	5.1	264.3	8.1	8641.	1283.	1068.	232.0	7725.	
EXCESSH SECTION	1.8	256.2	3.0		1289.	1253.	232.0		
TOTAL BOILER	25.0	* 253.2	41.3		* 1289.	* 1253.		245344.	

* - EXIT PARAMETERS

NAK FLOW TOTAL LB/HR	NAK FLOW NET LB/HR	MERCURY FLOW LB/HR	ENTHALPY CHANGE NAK BTU/LB	ENTHALPY CHANGE HG BTU/LB	THERMAL POWER KW	HEAT LOSS EXTERNAL KW	PINCH POINT DT DEG.F	TERMINAL NAK-HG DT DEG.F	VAPOR SUPERHEAT DEG.F
7093.	6379.	1666.	39.	146.	82.	8.	43.1	35.9	194.

THERMAL PASS RESISTANCES,MATERIAL CONDUCTIVITIES AND HG PASSAGE GEOMETRY

RCNF = 0.000219	HR-SQFT-DEG.F/BTU	NAK FILM	D1 = 0.670	INCH	HG TUBE ID
RCNT = 0.000153	HR-SQFT-DEG.F/BTU	SS TUBE	TTA = 0.040	INCH	TA WALL THICKNESS
RCST = 0.000440	HR-SQFT-DEG.F/BTU	STAGNANT NAK	TST = 0.100	INCH	STAGN.NAK THICKNESS(MEAN)
RCHT = 0.000079	HR-SQFT-DEG.F/BTU	TA TUBE	TSS = 0.035	INCH	SS WALL THICKNESS
RR = 0.000890	HR-SQFT-DEG.F/BTU	TOTAL OF ABOVE	D2 = 1.020	INCH	HG TUBE OD.

FMPP = 6.000	INCH	MPP PITCH	KSS =13.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,SS
N2 = 16.		NUMBER OF PASSAGES IN MPP	KNAK =15.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,NAK
DMPP = 0.080	INCH	PASSAGE WIDTH	KTA =40.00	BTU/HR-FT-DEG.F	CONDUCTIVITY,TA
HMPP = 0.032	INCH	PASSAGE HEIGTH(1)	DEMPP= 0.0752	INCH	DIA.EQ.,MPP
HHMPP = 0.072	INCH	PASSAGE HEIGTH(2)	ACMPP= 0.0051	SQINCH	CROSSECT.AREA
PHELIX= 2.000	INCH	SFHX PITCH	DEH = 0.5426	INCH	DIA.EQ.,SFHX
THICK = 0.001	INCH	SFHX STRIP THICKNESS	AH = 0.2873	SQINCH	CROSSECT.AREA
DBAR = 0.0	INCH	CENTER BAR OD	N1 = 1.		NUMBER OF TUBES

APPENDIX A

STAGNANT NAK THERMAL RESISTANCE IN OVAL-ROUND DOUBLE CONTAINMENT TUBE

Typical oval-round double containment tube cross section is shown in Figure A-1. It involves varying stagnant NaK thickness distribution around the circular tube. The stagnant NaK thickness distribution is dependent on the tube eccentricity ratio between the round and the oval tube. The eccentricity of the tubes results from the nonuniform thermal expansion of the tube materials when the oval-round tube bundle is coiled in helical configuration and heated to operating boiler temperature. Such a geometry creates nonuniform thermal resistance and a nonsymmetric temperature field between the flowing NaK and boiling mercury. The nonsymmetric temperature field also creates a natural circulation heat transfer effect of the stagnant NaK in the heat transfer pass. The description of the oval-round tube heat transfer pass shows that a complicated three dimensional heat transfer analysis must be employed to determine the true temperature conditions in the mercury flow passage. The complexity of both the heat transfer pass thermal conditions and the two phase flow heat and momentum transfer correlations result in extreme difficulty in applying a three dimensional analytical approach. For this reason, a one dimensional analytical design approach was selected. The heat flow between the primary and secondary fluids was assumed to be strictly radial. The equivalent wall thermal resistance of oval-round tube assembly was defined to account for nonsymmetric temperature field around the mercury flow passage.

In the concentric position (Fig. A-1,a), the stagnant NaK was considered to be of uniform thickness over entire periphery of the inner tube, such that the stagnant volume in the equivalent wall equals that of the actual wall. The volume of stagnant fluid is:

$$\begin{aligned} \text{Vol} &= (\pi\, r_3^{\,2} + 2\, r_3 \ell) - \pi\, r_2^{\,2} \\ &= \pi\,(.38)^2 + (.38)(.27) - \pi\,(.375)^2 \\ &= .218\ \text{in}^2 \end{aligned}$$

The equivalent uniform thickness is then found from

$$\text{Vol} = 2\pi\,(r_2 + \frac{\Delta r}{2})\,\Delta r$$

whence

$$\Delta r = .0835\ \text{in.} \cong .100\ \text{in.}$$

The thermal resistance of the equivalent stagnant NaK thickness referenced to mercury tube I.D. is then

$$R_{concentr} = \frac{r_1}{\bar{r}} \frac{\Delta r}{12\ K_{st}} = .00044\ \frac{hr\text{-}ft^2\text{-}°F}{btu}$$

where $\bar{r} = \dfrac{r_3 - r_2}{\ln (r_3/r_2)}$

r_1 = .335 in. Ta tube I.D.

r_2 = .375 in. Ta tube O.D.

r_3 = .395 in. Analytical stagnant NaK containment tube I.D.

K_{st} = 15 but/hr-ft-°F

The thermal resistance through maximum eccentrically situated oval-round tube geometry is treated by assuming inner and outer tubes as being concentric over some fraction of the periphery, say 60%, and the remainder (40%) as being comprised of concentric walls separated by stagnant NaK at the maximum eccentricity. For that particular case (Fig. A-1,b), the stagnant NaK thicknesses and their thermal resistances are:

$$\Delta r_1 = r_3 - r_2 = .380 - .375 = .005 \text{ in.}$$

$$R_1 = \frac{r_1}{\bar{r}_1} \frac{\Delta r_1}{12\ K_{st}} = \frac{.335}{.3778} \frac{.005}{(12)(15)} = .0000246\ \frac{hr\text{-}ft^2\text{-}°F}{btu}$$

$$\bar{r} = \frac{\Delta r_1}{\ln(r_3/r_2)} = \frac{.005}{\ln 1.013} = .3778 \text{ in.}$$

and

$$\Delta r_2 = r_3' - r_2 = .895 - .375 = .520 \text{ in.}$$

$$R_2 = \frac{r_1}{\bar{r}_2} \frac{\Delta r_2}{12\ K_{st}} = \frac{.335}{.597} \frac{.520}{(12)(15)} = 00162\ \frac{hr\text{-}ft^2\text{-}°F}{but}$$

$$\bar{r}_2 = \frac{\Delta r_2}{\ln (r_3{}^1/r_2)} = \frac{.520}{\ln 2.39} = .597 \text{ in.}$$

Lumping the two resistances in parallel resistance network, the overall thermal resistance is calculated as follows:

$$\frac{1}{R_{eccentr.}} = (.06)\ \frac{1}{R_1} + (.4)\ \frac{1}{R_2}$$

$$= 24390 + 2469$$

$$= 26859$$

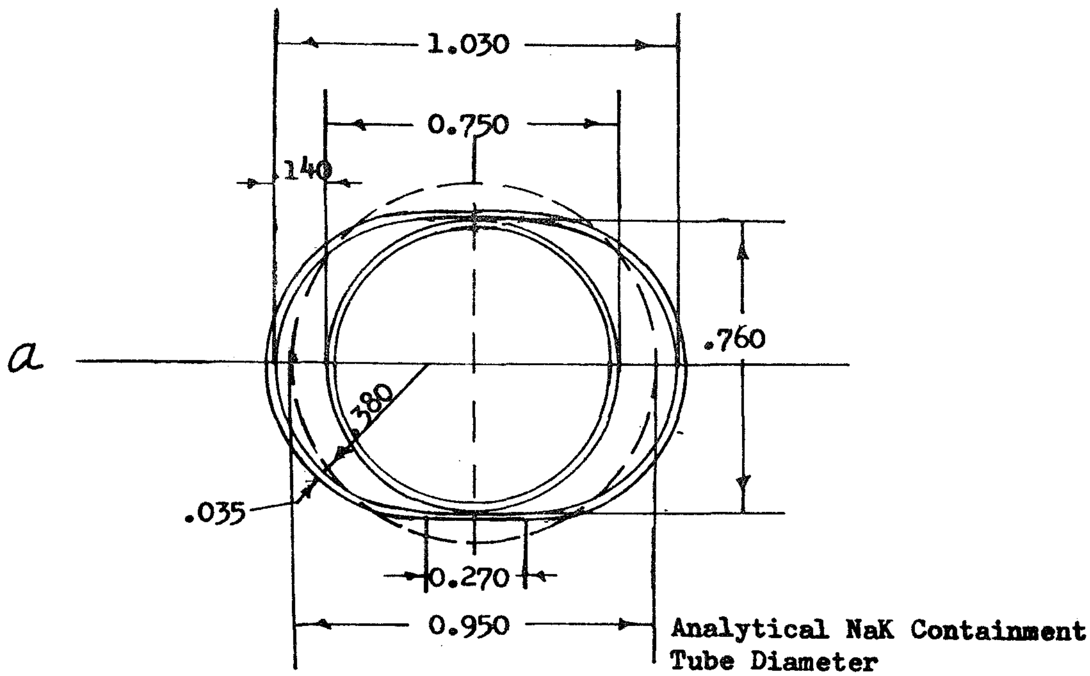
$$R_{eccentr.} = .000043\ \frac{hr\text{-}ft^2\text{-}°F}{btu}$$

The comparison of thermal resistance approximations of oval/round tube concentric ($R_{concentr.}$) and eccentric ($R_{eccentr.}$) geometries shows that

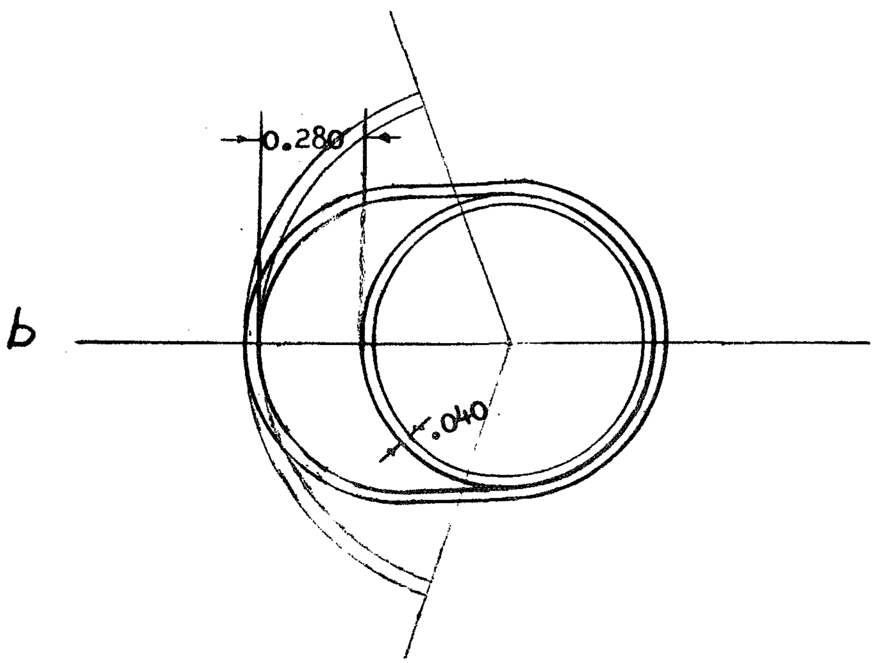
$$R_{eccentr.} \approx (.1)\ R_{concentr.}$$

Based on this approximation, it seems credible that any tube horizontal eccentricty reduces the stagnant NaK thermal resistance from the maximum value when the tubes are in concentric position. For this reason, the utilization of $R_{concentr.}$ = .00044 hr-ft^2-°F/btu in local boiling heat transfer analysis throughout the boiler length can be considered as a reasonable conservative value.

CROSS SECTION OF DOUBLE CONTAINMENT TUBE



CONCENTRIC
MERCURY TUBE POSITION



ECCENTRIC
MERCURY TUBE POSITION

Figure A-1